DEVELOPMENT AND TEST OF A Nb$_3$Sn RACETRACK MAGNET USING THE REACT AND WIND TECHNOLOGY

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ABSTRACT

Fermilab is involved in the development of a high field accelerator magnet for future hadron colliders using Nb$_3$Sn superconductor and the react and wind technology. The magnet design is based on single-layer common coils wound simultaneously into a laminated mechanical structure and impregnated with epoxy. In order to develop and optimize the fabrication techniques and to study the conductor performance, a magnet with simple flat racetrack type coils in a common coil configuration was assembled and tested. The coils were wound in the mechanical structure and in situ impregnated following a procedure that will be used in the single-layer common coil. Reacted Nb$_3$Sn Rutherford-type cable with 41 strands each with a 0.7 mm diameter, has been used. The magnetic and mechanical design of the racetrack magnet, the fabrication techniques and the test results are presented and discussed in this paper.

INTRODUCTION

The main dipoles of post-LHC hadron colliders will require the adoption of new materials (instead of NbTi) and/or new fabrication technologies in order to keep the collider cost within acceptable limits. Many different options are under study in the US including common coil and block type dipoles [1-3] using Nb$_3$Sn at 4.2 K, and a superferric transmission line magnet using NbTi at 6-7 K [4]. High temperature superconductors are also under investigation [5] but their adoption in an accelerator dipole model appears far away. At Fermilab an intense R&D program is underway aiming at low cost 10-11 T dipole magnets using Nb$_3$Sn operating at 4.2 K. Two designs are under development: a two-layer cos-theta dipole fabricated according to the wind-and-react technology [6] and a single-layer common coil dipole fabricated with the react-and-wind technology [7].
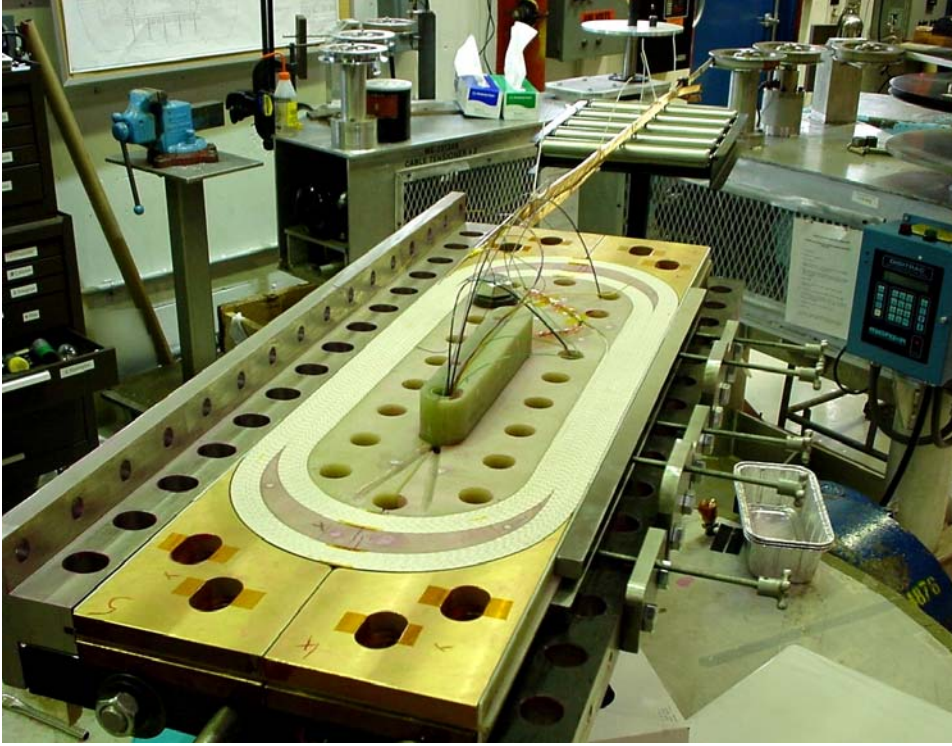
FIGURE 1. Racetrack magnet during assembly of the mechanical structure. On the right: clamps and side bars used during winding. On the left: final side pusher. The tensioner is shown in the top right corner.

The react-and-wind technology has many potential cost savings in the insulating materials (Kapton and E-glass can be used instead of S2-glass), in the structural materials (inserts can be made of G10 or Ultem), and in the fabrication technology (after assembly the coils have to withstand only a moderate heat treatment for epoxy impregnation at 120 C, instead of a heat treatment at 650-700 C to make the Nb_3Sn).

The react-and-wind technology as to date yielded mixed results despite intense efforts [8]. Recently the common coil concept [9], with its conductor friendly approach, has opened a promising new season for this technology. In order to explore this field Fermilab is involved in a large R&D effort: first, a conductor development program was started in collaboration with LBNL [10], aiming at the development of an optimal conductor for the application of this technology to our target magnet; secondly, a racetrack magnet with two flat coils in a common coil configuration was assembled and tested; finally a single-layer common coil dipole has been designed and fabrication is underway. The single-layer common coil has collars reinforced by transversal bridges set between coil blocks [7]. These bridges are installed during winding requiring the coils to be wound simultaneously into the collars and in-situ impregnated. The racetrack was designed in order to gain experience with these fabrication techniques. In this paper the design of the racetrack, its assembly and test results are presented and discussed.

TABLE 1. Conductor characteristics

Parameter	Unit	Value
Material		Nb_3Sn
Cable type		Rutherford
Dimensions	mm^2	15.05x1.218
Strand diameter	mm	0.7
Number of strands		41
Strand quench current at 10 T 4.2 K	A	400
Ic expected total degradation		20 %
Cu/non-Cu		0.62

MAGNET DESIGN

The magnet (HFDB-01) consists of two flat racetrack coils, wound using a pre-reacted Nb$_3$Sn cable and connected by a NbTi cable. The magnet was designed to:

❖ achieve a field between 9 and 10 tesla in order to study the behavior of coils fabricated with the react-and-wind technology by comparing the critical current degradation in the magnet with the degradation measured on wire and cable short samples.

❖ develop fabrication techniques that will be used for the single-layer common coil: cable heat treatment, insulation and winding of pre-reacted coil, and winding and impregnation of coils inside the mechanical structure.

The cable design (see table 1) is the result of a conductor development program that showed the possibility of a total critical current degradation (cabling + bending + transverse pressure) lower than 20% using strands with a diameter of 0.7 mm and a minimum bending radius in the magnet end of 90 mm [10]. In short sample tests, cables with a stainless steel core showed the possibility of higher bending degradations than cables without a core. For this reason, the cable used in the racetrack has no core.

The wire has been produced by Intermagnetics General Corporation (IGC) using the internal tin diffusion process. It has 19 sub-elements and a hexagonal Ta barrier. The copper over non-copper ratio (Cu/non-Cu) is 0.61:1. Short samples measured after a heat treatment of 200 hours at 575 C and 40 hours at 700 C showed stability problems below 13 T. The critical current was 325 A at 13 T and 4.2 K. The quench current was about 400 and 560 at 12 and 10 T respectively. The effective filament diameter was about 176 μm and is suspected to be, together with the low Cu/non-Cu value, the cause of the conductor instability at field lower than 13 T.

The cables used to wind the magnet were heat treated according to the following plan: ramp at 6 C/h up to 215 C, on hold for 175 h; ramp at 15 C/h up to 340 C, on hold for 120 h; ramp at 25 C/h up to 575 C, on hold for 160 h; ramp at 25 C/h up to 700 C, on hold for 30 h. The steps at 215 and 340 C were inserted in order to avoid tin leakage. The time spent at maximum temperature (700 C) was reduced in an unsuccessful attempt to improve the conductor stability at 10 T. Five wire short samples were heat treated together with the cable. Because of the instability of the conductor, the lowest quench current was selected as the short sample limit. One sample was rejected because its current was significantly lower than the current of all other samples. The cabling degradation was measured by comparing the quench current of short sample strands extracted from the cable, with the quench current of virgin strands. The cabling degradation was about 16 % at 12 T. The bending degradation of wires was measured using the technique reported in [11]. The results showed a very low degradation (2 %) at a maximum bending strain of 0.23 % and a larger degradation (14 %), closer to expectations, at a maximum bending strain of 0.46 %. A possible explanation of this behavior is that the current carrying capability of the conductor at 10 T would be higher if not limited by its instability. The degradation caused by bending starts from this higher threshold.

The magnetic design is summarized in table 2. The straight section is 400 mm long and consists of 29 turns in a single block. In the ends the minimum radius is 90 mm, and a spacer is set between the fifteenth and the sixteenth turn. A 5 mm-thick G10 plate separates the coils. The magnet contains no iron because a simple mechanical structure was preferred to a larger and more complicated structure, which would allow iron in close proximity to the coils (iron outside the mechanical structure would have a very low efficiency). The maximum field in the coil (9.03 T) is in the center (i.e. fifteenth turn) of the straight section. The magnetic force directed toward the main plates, at 9 T, is 1.81 MN.
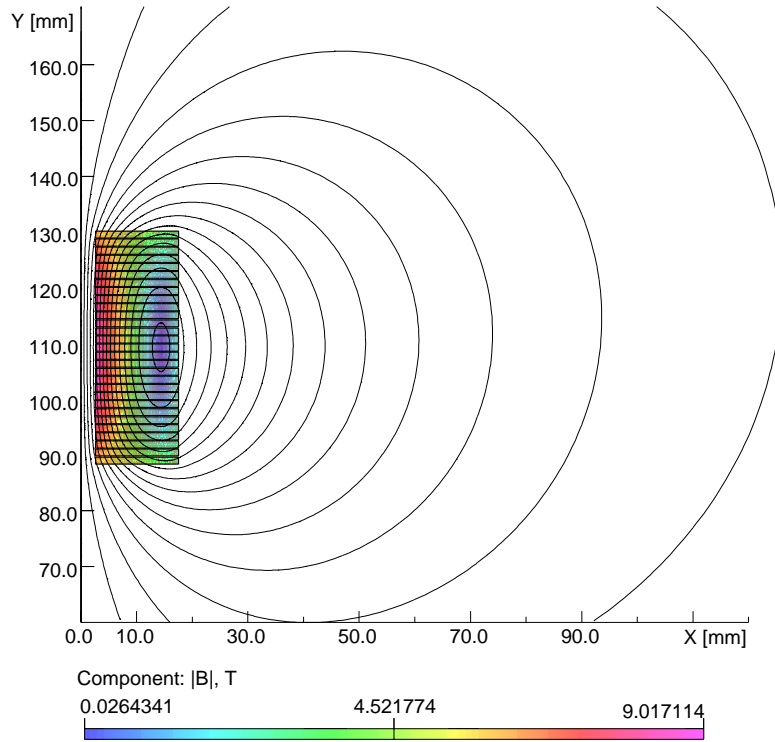
FIGURE 2. Cross section of a coil. Magnetic field is shown at maximum current.

TABLE 2. Magnet parameters

Parameter	Unit	Value
Maximum field in the gap	T	9
Maximum current	kA	14.3
Gap between coils	mm	5
Number of turns per coil		29
Minimum radius in the ends	mm	90
Total conductor area in the cross section	cm^2	2x9.15
Transfer function	T/kA	0.625
Total inductance	mH	0.331
Total stored energy @ 9 T	kJ	34.32
Normal force on the main plate @ 9 T	MN	1.81

HFMB-01 can be protected using current extraction or quench heaters.

Each quench heater consists of a 25 μm-thick stainless steel sheet, glued on a Kapton foil (75 μm thick). The heater is shaped to cover the entire coil, except for the two outermost turns. A second Kapton foil is placed between the heater and the coil, and a third one on the top of the heater. A heater is set between a coil and the G10 plate. The other heater is placed between the other coil and the mechanical structure. The different locations will be used to study the heater efficiency under different conditions. The field in the coil side close to the inner heater is higher than the field in the coil side close to the outer heater. On the other hand the thermal contact with the coil should be better for the outer heater than for the inner heater due to the magnetic forces.

With 30 mΩ dump resistance and no heaters, assuming 7 ms for quench detection, the computed peak voltage is 420 V, and the maximum temperature is 55 K. Without a dump resistor, assuming the heaters to be effective 30 ms after the start of the quench, the calculated peak temperature is 180 K and the peak voltage is 90 V.
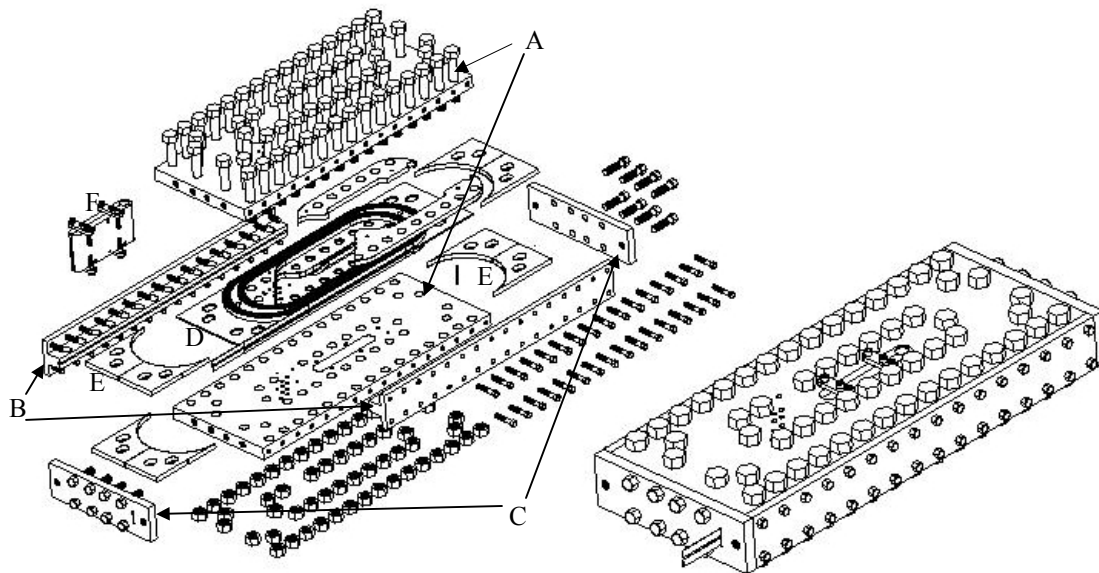
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FIGURE 3. Racetrack assembly. See text for details.

MECHANICAL DESIGN

The main components of the mechanical structure are two 40 mm thick stainless steel plates ("main plates" in the following, indicated by A in Figure 3), which provide pre-stress and support of the main component of the magnetic force (in the direction normal to the coil plane). 57 stainless steel bolts, with a 25 mm diameter, (pre-loaded at 2700 Kg after magnet impregnation) should restrain the coil separation within 0.2 mm at maximum field. Side pushers (B) provide vertical pre-stress and support by means of 32 bolts, each with 12 mm diameter. In the ends pre-stress and support are given on each side by a 25 mm-thick plate (C) and 8 bolts, each with a 20 mm diameter. All plates, pushers and bolts are made of non-magnetic stainless steel. A 5 mm-thick G10 plate (D) separates the coils. End saddles (E) are made of brass. All parts inside the coils, both in the ends and in the straight section, are made of G10. The NbTi cable connecting the coils is pre-shaped around a G10 road and closed inside a G10 block (F). Pins are used to center the coil inserts and the inter-coil plate on the top of the main plate.

MAGNET ASSEMBLY

(i) Heat treatment and insulation: Two 60 m long cables were wound on single-layer metallic spools (resulting in a pancake-like winding), together with a mica-glass tape, in order to prevent sintering during the heat treatment. After the heat treatment, performed in an Argon atmosphere inside a retort, the cables were insulated using a 75 μm-thick 12.5 mm wide E-glass tape with 35% overlap. Rollers were set very close to the insulation application point in order to prevent strands from popping out and to protect the reacted cables. During insulation and winding the cables were straightened but never bent in the direction opposite to the bending during the heat treatment. The bending strain was minimized by using spools for the heat treatment with a diameter (360 mm) twice the minimum diameter in the coil ends (180 mm, as in the single-layer common coil magnet [7]).

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(ii) Winding and assembly: The coil side of the main plates was covered by three layers of 125 μm-thick Kapton films used for ground insulation. A main plate served as the winding table and the G10 coil inserts, fixed by pins, were used as the winding mandrel. The Nb_3Sn cable was spliced to the layer-connecting NbTi cable, and a copper strip was added to each side of the splice. These copper strips serve as thermal stabilizers during magnet operation as they are in direct contact with helium through holes in the main plates. The coils were wound using a tensioner modified in order to have a feedback control of the tension (10 kg) without any backward bending of the cable. A quench heater was set between the first coil and the G10 inter-layer plate. This plate was then used as the winding table for the second coil. A second heater was set between this coil and the top main plate. After winding each coil, the Nb_3Sn cable was spliced to two NbTi cables and a copper strip was added to each side of the splice. The splices are completely inside the magnet (epoxy impregnated) and the strips are used for thermal stabilization. The Nb_3Sn cable was not cut outside the splice. It was kept between the NbTi cables and the three cables were connected to the current leads of the test facility. Temporary side bars along each side of each coil and clamps connected to the bottom main plate were used in order to keep cables in position during winding (see Figure 1). After winding, the side pushers and the end plates were installed and used to compact the coils.

(iii) Impregnation and prestress: After assembly, the magnet was vacuum impregnated with epoxy. All parts of the supporting structure (main plates, side pushers, end plates), and the end saddles, were painted with mold-release on all sides before winding. Silicon-RTV was used to fill the cooling channels for the internal splices (and removed after impregnation), and to preserve the flexibility of the NbTi cable by protecting it from epoxy. All bolts were painted with mold-release, greased and protected with silicon-RTV. Impregnation was performed in a bath by slowly filling a slightly inclined box, which contained the magnet. After impregnation the external surface of the magnet was cleaned of epoxy, all bolts were extracted, cleaned, re-inserted and prestress was applied.

(iv) Instrumentation: The magnet was instrumented with voltage taps, temperature sensors and strain gauges. The original design foresaw voltage taps only close to all splices. During winding it was decided to introduce more voltage taps for quench start location and quench protection study. The interlayer plate was modified in order to introduce channels for the voltage taps' wiring. Four voltage taps on each end were introduced plus three on the outer cable of a coil located close to a spot heater (unfortunately lost when prestress was applied). After impregnation two Cernox temperature sensors were located on the right and left edge of the G10 inter-layer plate close to the coils. Four bolts in the center of the main plates, two bolts in the center of each side pusher and two bolts on each end plate were instrumented with two strain gauges on each bolt. All gauges were calibrated at room temperature and at 4.2 K. Six more gauges were located close to the reading gauges for magnetic field compensation.

TEST RESULTS

HFDB-01 was tested at Fermilab in the vertical magnet test facility [12] at 4.5 and 3.5 K, with three ramp rates (20, 300 and 500 A/s). A 30 mΩ dump resistance was used for protection.

The quench history is shown in Figure 4. After the first quench (8700 A), the quench detection system threshold was increased (from 0.3 V to 0.7 V) because spikes were triggering the protection system even when no real quench was developing. The second quench occurred at 8220 A with a ramp rate of 300 A/s. Three quenches at 20 A/s occurred
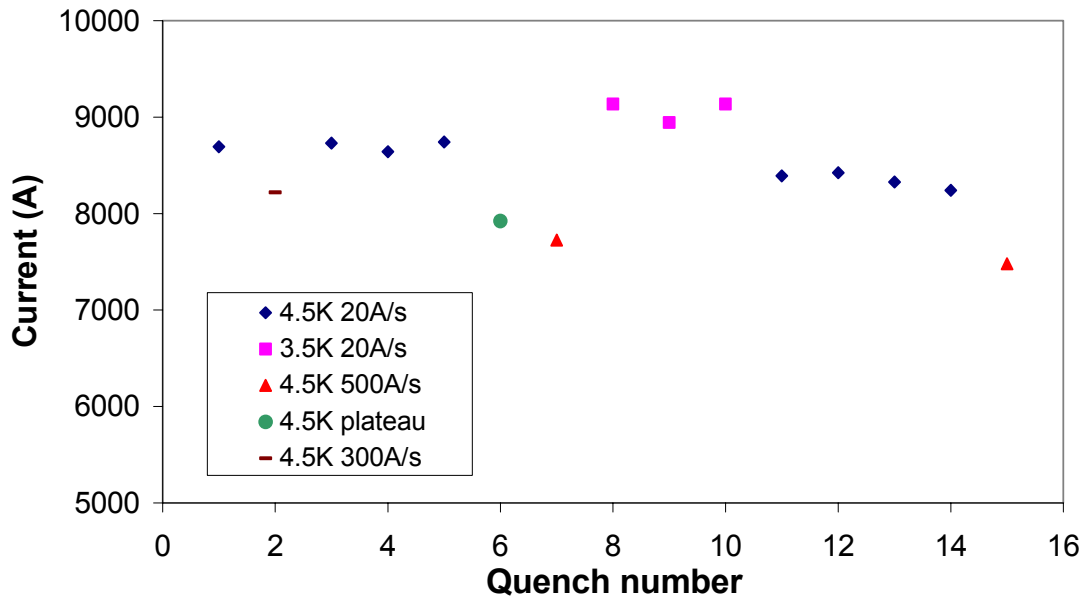
FIGURE 4. Quench history. See text for details

between 8641 and 8742 A, which indicated a "noisy" plateau. Voltage spikes were randomly present during all current ramps indicating possible coil displacements. These displacements could be the source of significant heat, and therefore the next run was planned with a ramp up to about 8000 A at 20 A/s, a 15 minute interval at constant current (in order to dissipate the heat produced during the ramp), and a second ramp at 20 A/s. A quench occurred at 7922 A after eight minutes at constant current. Subsequently, a fast ramp at 500 A/s gave a quench at 7725 A.

The magnet was then cooled down at 3.5 K and three quenches occurred at 9136, 8944 and 9136 A. It should be noted that the second quench was at a slightly higher temperature than 3.5 K. Four more quenches at 4.5 K occurred between 8240 and 8440 A with a 20 A/s ramp. The last quench was at 7478 A with a ramp of 500 A/s.

All quenches except the second were located in the same coil (bottom coil), and all quenches at the 20 A/s ramp rate started within the same voltage tap pair. Unfortunately this pair included the second to the fifteenth turns of the bottom coil (the first turn is the outermost one). The analysis of quench propagation indicated that some quenches started in or close to the ends. The others could not be located.

Analysis of the quench data showed in almost all quenches a voltage spike before or at the beginning of the voltage rise indicating the quench. Therefore many quenches, if not all, could have been caused by the energy released by a coil movement.

It can be noted that all quenches at the second 4.5 K cycle occurred at a lower current than the quenches at the first 4.5 K cycle. This could be the sign of a conductor degradation or of a deteriorated mechanical behavior after the quenches at 3.5 K. Analysis of the strain gauge data showed that the end plates were unloaded at all currents, while the bolts on the main and side plates showed a linear increase of the load with the current. Another cycle of measurement has been planned in order to test the magnet performances with a better support in the ends. The prestress in the end plates will be increased after warming up the magnet without disconnecting it from the test facility. Measurement of splice resistance and more ramp rate studies are also planned for the second cycle.

One strip heater was lost during pre-tests, the other was used for quench protection. It was not possible to perform heater study, because the inductive signal generated by firing

the heater triggered the quench detection system. We will attempt to fix the second heater before the second cycle and to connect it in such a way that the inductive signals from the two heaters will cancel. A heater design with higher resistance and lower inductance will be adopted in the next model to test the heater efficiency.

CONCLUSIONS

A racetrack magnet was fabricated using Nb_3Sn and the react-and-wind technology. Procedures were developed and applied in order to minimize the cable bending during insulation and coil winding. Coils were wound inside the mechanical structure and in-situ impregnated. Measurement during the first thermal cycle revealed a degradation of 39% compared with the maximum current estimated from short sample data. Voltage spikes during current ramp indicate possible coil displacements due to magnetic forces. Neither end plate showed any load and a poor support in the ends is suspected to be the cause of these displacements. A second thermal cycle is planned after increasing the pre-load in the ends.

ACKNOWLEDGEMENTS

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